

Investigation of Modulated Laser Techniques for Improved Underwater Imaging

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LONG-TERM GOALS

The ultimate goal of this program is to determine the benefits and limitations of using modulated optical signals to image underwater objects and to compare this approach with existing underwater imaging techniques.

OBJECTIVES

The objective of this program is to investigate the application of modulated laser techniques to improve the contrast and resolution of underwater imaging systems. Specifically, the goals of the program are as follows:

1. To determine how the optical properties of water affect the propagation of a modulated optical signal.
2. To quantify under what conditions (i.e., system configuration, water quality, object characteristics) this approach improves underwater imaging.
3. To compare this approach with more traditional laser imaging systems, such as laser line scanner and range-gated systems.

APPROACH

This project will focus on the theoretical and experimental analysis of modulated laser approaches for improving underwater imaging. Tools developed in a previous program (“Application of Hybrid Lidar-Radar Technology to a Laser Line Scanner”) will be used to determine the effect of water optical properties and system characteristics on the propagation of a modulated optical signal in water. The general approach will be to carefully measure the optical properties of the water (scattering and absorption) and characterize the system components (optical receiver, modulated laser transmitter, target properties), use these variables as inputs to a theoretical model, and use the model to determine how the contrast and resolution of an image is affected by the modulation. Dr. Eleonora Zege at the National Academy of Sciences, Belarus, in FY01 developed the fundamental theory needed for this model. A user-friendly version of this model will be developed so that the various inputs (water optical properties, system characteristics, target geometry) can be easily varied to determine the effect on the modulated system performance. Concurrent with the modeling effort, experiments will be performed and the data will be compared to the theoretical predictions. These experiments will be used to validate the model so that it can be used to predict the performance of more sophisticated systems.

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WORK COMPLETED

The first task completed was the development of a program, Modulated Vision System (MVS), that simulates the performance of underwater, modulated laser imaging systems. This software runs on Win32 platforms and has an interactive, user-friendly interface. The inputs to the MVS program include:

1. system configuration (modulated or non-modulated, focal plane array or synchro-scan),
2. system geometry (source-receiver separation, receiver-object distance, object-bottom distance),
3. source parameters (optical power, wavelength, aperture size, divergence, modulation frequency),
4. receiver parameters (aperture, field of view, optical transmission, detector quantum efficiency, number of pixels),
5. target characteristics (size, shape, reflectivity), and
6. water characteristics (beam attenuation coefficient, single scattering albedo, scattering phase function).

With these inputs, the program simulates images observed by a modulated or a non-modulated laser imaging system. Additional program outputs include plots of the frequency dependencies of the total signal, backscatter noise, and image contrast that are useful for understanding the effect of modulation frequency on system performance.

Controlled laboratory tank experiments were conducted to complete the second task and the first step in validating the MVS program. The experimental setup includes a 5 watt, 532 nm laser that is modulated at frequencies from 10-100MHz, and a photomultiplier tube optical receiver. Other details of the experimental setup have been described elsewhere [1]. A diagram of the experimental setup is shown in Figure 1. In the experiment, the target shown in Figure 1 was scanned across the plane of intersection of the source and receiver to obtain one slice of the target image (represented by the dotted green line across the center of the target) at each modulation frequency. Since the MVS program also has the capability to process a slice of the target image, the two data sets were compared directly. Different concentrations of Maalox antacid in water were used to change the water turbidity, and the scattering and absorption properties of the water were measured with a WETLabs AC-9 Instrument. The scattering phase function for Maalox was also measured [2, 3] and was used as an input to the MVS program. The receiver field of view (FOV) was also varied from 0.5 to 5.5 degrees to study its effect on the system performance.

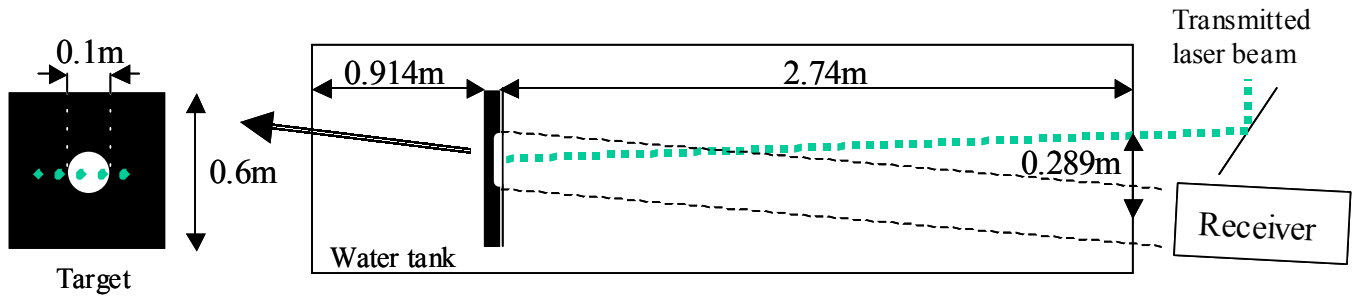


Figure 1. Diagram of the experimental setup used to validate the MVS program.

RESULTS

The data sets shown in Figures 2 and 3 were obtained with a narrow receiver field of view setting (0.5 degrees). In Figure 2, the experimental and MVS program results are shown for a beam attenuation coefficient of 1.2m^{-1} . In each case, the data is normalized to the amplitude of the signal at the target center (center of the white circle shown in Figure 1). Both the non-modulated (points '0MHz') and the modulated data is plotted to illustrate the effect of modulation frequency on the target contrast. It is evident in both the model and experimental data that the contrast between the white and the black parts of the target is relatively high and is the same for both the non-modulated and the modulated signals.

The second data set shown in Figure 3 was obtained with an increased Maalox concentration resulting in a beam attenuation coefficient of $c=2.2\text{m}^{-1}$. The simulated and experimental data show a steady increase in target contrast for frequencies greater than 10MHz. The exception to this trend is the 30MHz data where the contrast is reversed. This result is due to the interaction between the strong backscatter return and the signal reflected from the target. When these two signals are approximately equal in amplitude and are either in-phase or 180 degrees out of phase they either constructively or destructively interfere with each other [3].

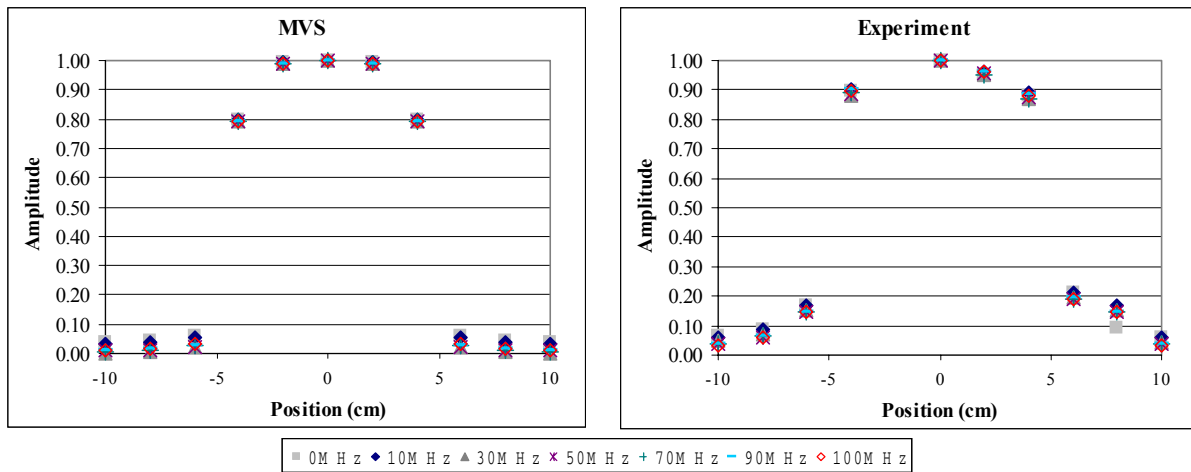


Figure 2. Comparison of model (MVS) and experimental results obtained with a receiver field of view of 0.5 degrees and $c=1.2\text{m}^{-1}$.

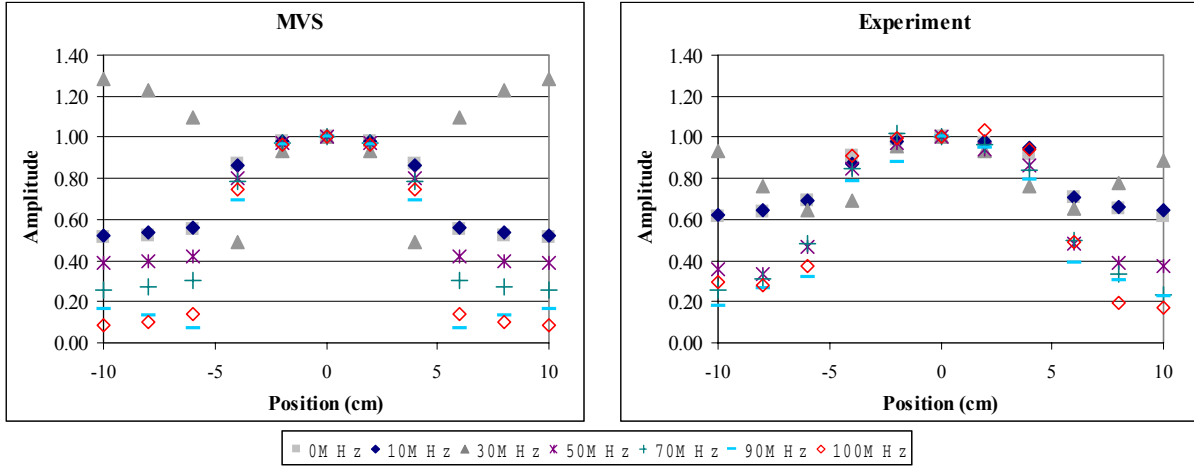


Figure 3. Comparison of model (MVS) and experimental results obtained with a receiver field of view of 0.5 degrees and $c=2.2m^{-1}$.

A summary of the data in Figures 2 and 3 is shown in Figure 4a where the contrast between the white and black portions of the target is plotted as a function of modulation frequency. The contrast was calculated as: $Contrast = (A_{white} - A_{black}) / (A_{white} + A_{black})$, where A_{white} is the signal amplitude at the center of the object (position '0' in Figures 2 and 3) and A_{black} is the signal amplitude at the edge of the object (position '10' in Figures 2 and 3). The trends in the narrow field of view data discussed previously are clear: the contrast is relatively flat as a function of frequency for the cleaner water and increases for frequencies above 30MHz for the more turbid water. The 'dip' in the contrast frequency response at 30MHz for $c=2.2m^{-1}$ is also evident, as is the good correlation between the MVS program and experimental results.

Model and experimental data obtained with the same Maalox concentrations but with an increased receiver field of view (5.5 degrees) are shown in Figure 4b for comparison. The effect of increasing the receiver acceptance angle is a reduction in contrast at all modulation frequencies and both water types relative to the narrow field of view data (Figure 4a). The effect of the destructive interference between the backscatter and target returns is also seen in the $c=2.2m^{-1}$ data where a 'dip' is observed in the contrast frequency response. As with the narrow field of view data, the correlation between the MVS program and experimental trends is quite good.

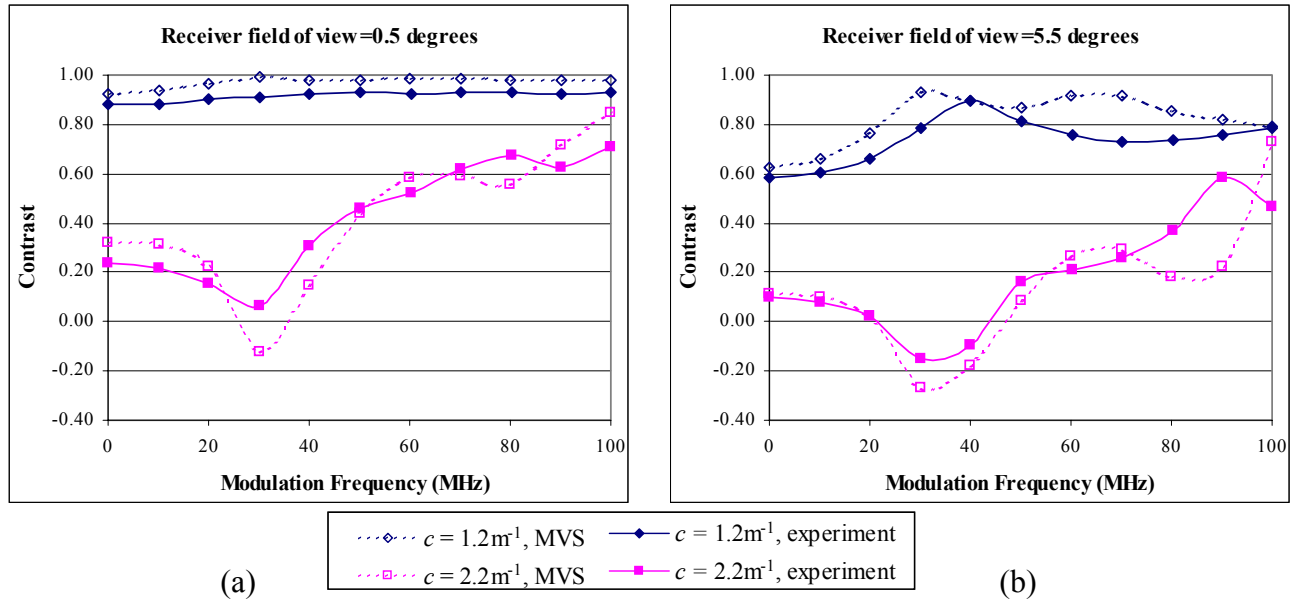


Figure 4. Plots of target contrast as a function of modulation frequency for different receiver fields of view (0.5 and 5.5 degrees) and different water clarities ($c=1.2$ and 2.2 m^{-1})

The impact of the modulation on image quality is shown in Figure 5 where the images produced by the MVS program for a field of view of 5.5 degrees and $c=2.2 \text{ m}^{-1}$ for a non-modulated system (0MHz) and at three different modulation frequencies are shown. The destructive interference effects at 30MHz produce an image similar to those obtained in a ‘shadow mode’ of detection. The contrast of the image produced at a 100MHz modulation frequency is significantly enhanced relative to the image for the non-modulated system and the 10MHz image. It is important to note that the effects of the frequency dependence of forward-scattered light have not yet been included in the MVS program. Therefore, the improvements in image contrast are due only to the modulation frequency dependence of the light backscattered from the water itself and its interaction with the light reflected from the underwater object.

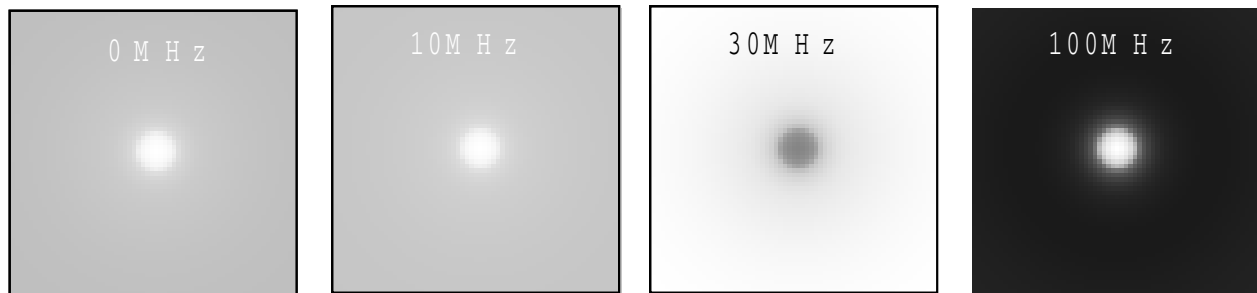


Figure 5. Simulated images produced by the MVS program for different modulation frequencies.

A summary of the significant results obtained in this project follows:

1. A Modulated Vision System (MVS) program has been developed to predict the performance of modulated underwater imaging systems as a function of water quality, target properties, and system characteristics.
2. Good correlation was observed between MVS program and experimental results for a controlled range of environmental and system parameters.
3. Use of the modulated laser approach resulted in improved target contrast in turbid water.

IMPACT/APPLICATIONS

Modulated laser imaging systems have the potential to improve the contrast and resolution of underwater images. The Modulated Vision System program developed in this project can be used to predict the performance of these systems and to determine under what conditions the use of this approach will enhance underwater images. The theoretical techniques that form the backbone of this program can also be used to study the application of the modulated technique to other scatter-limited imaging systems, such as those used to image through clouds, fog, and smoke and biological tissue.

TRANSITIONS

The results from this project have been used in the preliminary design of an AUV-mounted laser imaging system (Dr. Jules Jaffe, Scripps Institute of Oceanography). The purpose of this system is to provide extended range imaging (3-7 attenuation lengths) from an autonomous platform. The modulated laser imaging technique is currently being investigated for inclusion in this system to reduce backscatter noise and to improve depth resolution for locating low-contrast objects. There is also interest from the Missile Defense Agency (MDA) to use the modulated laser imaging approach to improve the detection of missiles in adverse weather conditions. The Modulated Vision System program developed in this project will be modified to include the optical properties of typical aerosols and clouds to determine whether the modulation approach can facilitate the MDA mission.

RELATED PROJECTS

Collaboration with researchers from the Scripps Institute of Oceanography has been initiated to study the potential for using the modulated laser imaging system in the AUV-mounted, underwater laser imaging system that they are developing. Visits at both Scripps and NAVAIR have occurred to closely study the implications involved in transitioning the modulated laser technology to the design of an autonomous underwater imaging system. Collaborative work has also occurred with the Electrical Engineering Graduate Department at Penn State University. Dr. Tim Kane and his student, Ms. Christine Coakley, are developing a bench-top volume scattering function instrument to study the scattering properties and of various scattering solutions, including Maalox and phytoplankton.

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